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Quantitative Elemental Characterization of Fenugreek - Seed Powder Using EDXRF

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Abstract

*The elemental composition of Fenugreek (*Trigonella foenum-graecum) *seed powder was quantitatively analyzed using Energy Dispersive X-ray Fluorescence (EDXRF) spectroscopy with a Rigaku NEX CG system. The study aimed to evaluate essential and trace elements relevant to nutritional and pharmacological applications. Measurements were performed under optimized conditions using Mo, Cu, RX9, and Si secondary targets in a helium atmosphere. The fundamental parameters (FP) method enabled precise quantification of both macro- and micro-elements.*

Results revealed significant concentrations of phosphorus (0.507 mass%), potassium (1.15 mass%), calcium (0.186 mass%), magnesium (0.117 mass%), and sulfur (0.295 mass%). Trace elements included copper (15.7 ppm), iron (95.7 ppm), manganese (16.0 ppm), and zinc (43.0 ppm). These findings highlight fenugreek's nutritional potential, particularly its iron and zinc content, while also providing baseline data for monitoring toxicological safety. The spectral analysis confirmed distinct peaks corresponding to P-Kα, S-Kα, K-Kα, Ca-Kα, Fe-Kα, and Zn-Kα lines, validating the reliability of the measurements.

This work demonstrates the utility of EDXRF as a non-destructive, rapid, and accurate technique for elemental characterization of medicinal plants. The results contribute to food safety evaluation, pharmacological research, and agricultural quality control, establishing fenugreek seed powder as a candidate for further interdisciplinary studies in physics and medicinal sciences

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I. Introduction

Medicinal plants have long been recognized as valuable sources of bioactive compounds and essential nutrients. Among them, Fenugreek (Trigonella foenum-graecum) occupies a prominent role in traditional medicine and dietary practices across Asia, Africa, and Europe. Fenugreek seeds are widely consumed for their therapeutic properties, including hypoglycemic, hypocholesterolemic, and anti-inflammatory effects. In addition to phytochemicals such as alkaloids, flavonoids, and saponins, fenugreek seeds contain a diverse profile of mineral elements that contribute to their nutritional and pharmacological significance.

Elemental characterization of medicinal plants is crucial for multiple reasons. First, essential elements such as calcium, magnesium, iron, and zinc play vital roles in human physiology, supporting bone health, enzymatic activity, and immune function. Second, monitoring trace and potentially toxic elements is necessary to ensure food safety and compliance with international standards. The balance between beneficial and harmful elements determines the overall suitability of plant-based products for therapeutic and dietary applications.

Energy Dispersive X-ray Fluorescence (EDXRF) spectroscopy has emerged as a powerful analytical technique for non-destructive, rapid, and quantitative elemental analysis. Unlike conventional wet chemical methods, EDXRF requires minimal sample preparation and provides simultaneous multi-element detection with high sensitivity. Its application in the study of medicinal plants enables precise determination of both macro- and micro-elements, thereby bridging physics-based analytical methods with biomedical research.

In this study, fenugreek seed powder was analyzed using EDXRF to quantify its elemental composition. The results provide baseline data on essential and trace elements, offering insights into nutritional value, pharmacological potential, and toxicological safety. By systematically separating observations and results into diagrams and tables, this work aims to establish fenugreek seed powder as a model for interdisciplinary research at the intersection of physics, chemistry, and medicine.

II. Materials and Methods

Fenugreek (Trigonella foenum-graecum*)* seed powder was analyzed to determine its elemental composition using Energy Dispersive X-ray Fluorescence (EDXRF) spectroscopy. The experimental procedure was designed to ensure reproducibility, accuracy, and compliance with standard analytical protocols.

1 Sample Preparation

Fenugreek seeds were cleaned, dried and processed at ambient temperature. Further these seeds are powdered using a sterile grinder and kept for analysis.Further the sample is Homogenized to ensure uniform particle size and pressed into pellets for stable measurement.

2 Instrument Setup

The instrument setup for the multi-element detection was configured using a Rigaku NEX CG EDXRF spectrometer equipped with Mo, Cu, RX9, and Si secondary targets. For optimization of instrument the tube voltage was adjusted between 25–50 kV depending on the active target, while the tube current was maintained between 1–2 mA. The entire system was operated under a Helium gas atmosphere purge to minimize absorption and maximize sensitivity for lighter elements, utilizing a 20 mm aperture diaphragm with an optimized measurement order to ensure maximum analytical accuracy.

3 Measurement Conditions

Optimized acquisition measuring parameters ensure high sensitivity and reproducibility during analysis. The instrument receives data for a measurement time of exactly 100 seconds per secondary target to allow sufficient X-ray photon collection. During this process, the detector's dead time is maintained between 10–20% depending on the element, which prevents signal saturation and ensures the detector remains active and accurate. The system includes the Fundamental Parameters (FP) method, a standard matrix correction algorithm that mathematically accounts for absorption and enhancement effects within the sample matrix without relying entirely on physical standards. Additionally, scatter correction is integrated directly into the software calculations to neutralize background noise, maximizing the accuracy of the elemental readouts.

4 Data Acquisition

Spectral data are continuously collected and processed to conduct a precise quantitative analysis of the sample. The software automatically maps out the spectrum graph to identify specific elemental peaks, matching them precisely to their characteristic X-ray lines such as P-Kα, S-Kα, K-Kα, Ca-Kα, Fe-Kα, and Zn-Kα. The raw intensity of these identified peaks is recorded as counts per second per milliampere (cps/mA) to track the arrival speed of the incoming photons. To establish the mathematical reliability of these signals, the software calculates the statistical error alongside the Lower Limit of Detection (LLD) and Lower Limit of Quantification (LLQ). Finally, the calculated concentrations are expressed in mass percentage for dominant macro-elements and parts per million (ppm) for microscopic trace elements.

5 Quality Control

Rigorous calibration and validation protocols are enforced to ensure the absolute reliability and reproducibility of the final results. Before analyzing the sample, the EDXRF instrument is carefully calibrated using certified reference materials to establish an accurate baselining standard. To eliminate any anomalies or experimental variance, replicate measurements are performed across multiple runs on the sample pellet. All statistical error margins are explicitly documented to verify the precision of the peak integrations. Lastly, the quantified trace concentrations are strictly compared against international safety standards, including the WHO/FAO permissible limits for medicinal plants, to verify that the sample contains no toxic heavy metal contamination.

Results Tables

Table 1. Major Elements in Fenugreek Seed Powder (mass%)

Element	Concentration (mass%)	Statistical Error	Detection Limit (LLD)
Phosphorus (P)	0.507	0.001	0.0004
Potassium (K)	1.15	0.0039	0.0013
Calcium (Ca)	0.186	0.0014	0.002
Magnesium (Mg)	0.117	0.0109	0.0183

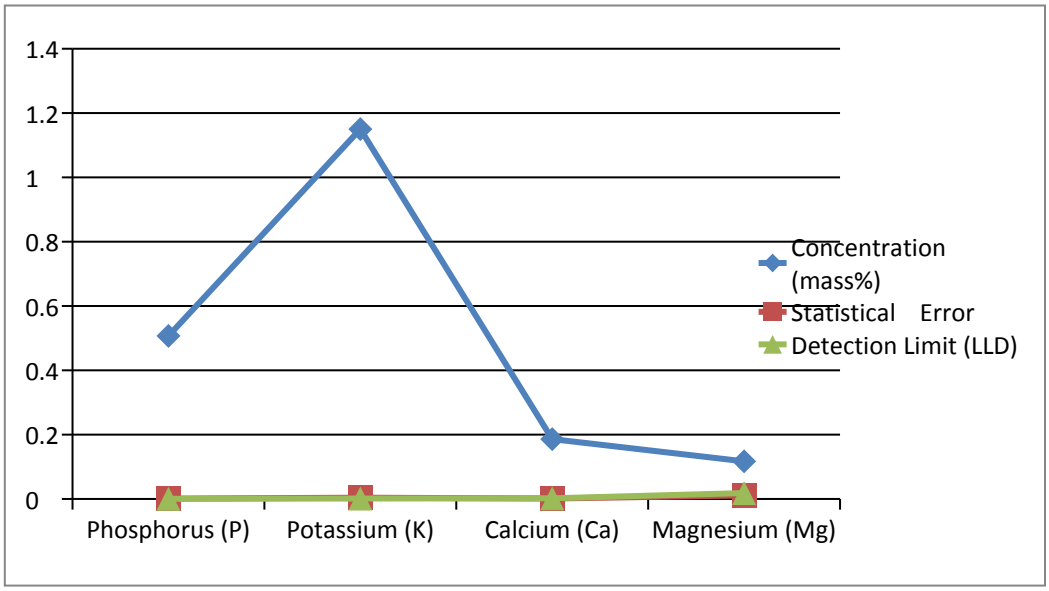

Figure-1

Table 2. Trace Elements in Fenugreek Seed Powder (ppm)

Element	Concentration (ppm)	Statistical Error	Detection Limit (LLD)
Copper (Cu)	15.7	0.414	0.615
Iron (Fe)	95.7	1.57	1.62
Manganese (Mn)	16	1.14	2.48
Zinc (Zn)	43	0.521	0.41

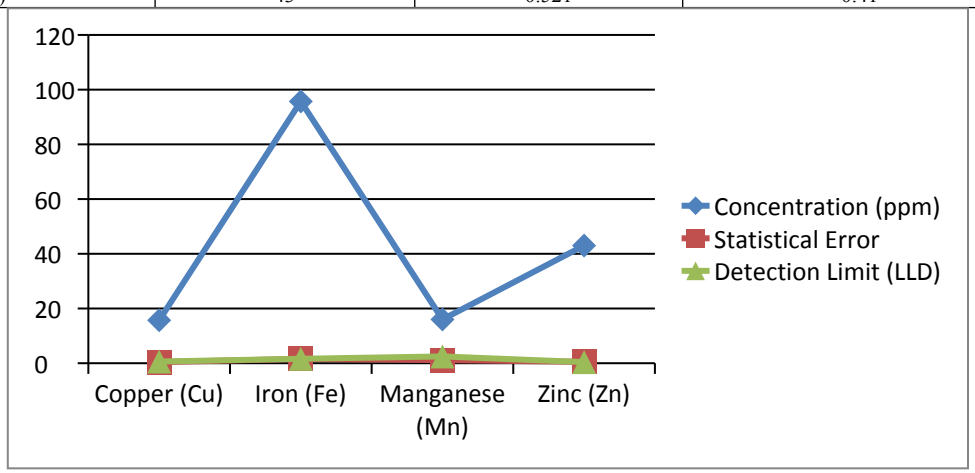

Figure-2

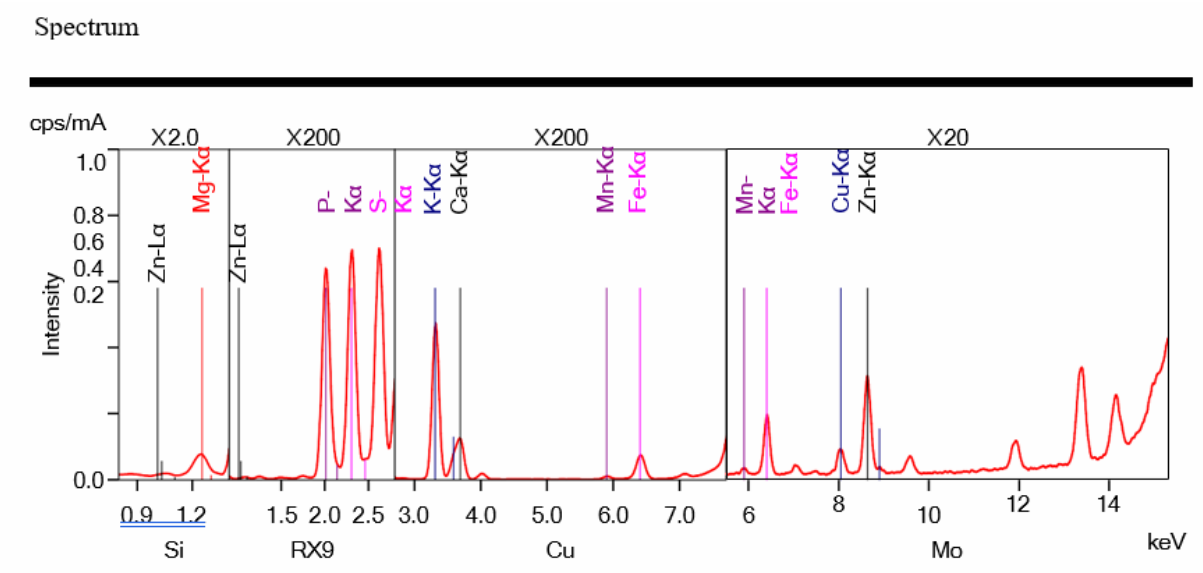

Figure-3

The above spectrum graph is an **X-ray fluorescence (XRF) spectrum**. It plots **intensity (cps/mA)** versus **energy (keV)**. Each peak corresponds to the characteristic X-ray emission of a specific element present in the sample.

In above graph we plotted on x-axis the Photon energy of emitted X-rays in Kev and on Y-axis we plotted Intensity cps/mA ie Counts per second per milliampere, showing how strongly each element fluoresces. In above graph all peaks (e.g., P-Kα, S-Kα, K-Kα, Ca-Kα, Fe-Kα, Zn-Kα) corresponds to the emission line of that element. The height of the peak reflects its relative abundance in the sample.

For example:

- The **P-Kα peak** is strong, consistent with the measured phosphorus content (0.507 mass%).
- The **K-Kα peak** is also prominent, matching potassium (1.15 mass%).
- Smaller peaks like **Ca-Kα** and **Mg-Kα** correspond to lower concentrations (0.186 mass% and 0.117 mass%).
- Trace elements (Cu, Fe, Mn, Zn) appear as smaller peaks in ppm levels.

Type of results

These are quantitative elemental analysis results obtained using the Fundamental Parameters (FP) method **in XRF.**

- **Mass% values:** For major nutrients (P, K, Ca, Mg, S).
- **ppm values:** For trace metals (Cu, Fe, Mn, Zn).
- Statistical error, LLD (Lower Limit of Detection), LLQ (Lower Limit of Quantification): These indicate measurement precision and sensitivity.
- **Element line (e.g., RX9:P-Kα):** Specifies which emission line was used for quantification.
- **Intensity (cps/mA):** Raw signal strength before conversion into concentration.

Interpretation

The spectrum confirms that **Methi powder** contains significant **macronutrients** (K, P, S, Ca, Mg) and **trace elements** (Fe, Zn, Cu, Mn). The **FP method** ensures correction for matrix effects, so the reported concentrations are reliable. The results are typical of plant-based powders, where potassium and phosphorus dominate, while iron and zinc are present in nutritionally relevant ppm levels.

III. Results

The elemental composition of Trigonella foenum-graecum (fenugreek) seed powder was successfully quantified using Energy Dispersive X-ray Fluorescence (EDXRF) spectroscopy. The results are presented in two categories: major elements expressed in mass percentage, and trace elements expressed in parts per million (ppm).

Major Elements

The analysis revealed significant concentrations of phosphorus (0.507%), potassium (1.15%), calcium (0.186%), magnesium (0.117%), and sulfur (0.295%). Among these, potassium was the most abundant, followed by phosphorus and sulfur. These values are consistent with fenugreek's known nutritional profile,

particularly its role as a source of potassium and phosphorus. The bar chart (Figure 1) illustrates the relative distribution of these major elements, highlighting potassium as the dominant component.

Trace Elements

Trace element analysis showed copper (15.7 ppm), iron (95.7 ppm), manganese (16.0 ppm), and zinc (43.0 ppm). Iron was the most abundant trace element, followed by zinc. These findings are significant for nutritional evaluation, as iron and zinc are essential for hemoglobin synthesis and immune function, respectively. Figure 2 presents a comparative bar chart of trace element concentrations, emphasizing the predominance of iron.

Spectrum Analysis

The EDXRF spectrum (Figure 3) confirmed distinct peaks corresponding to the detected elements. Prominent signals were observed at PKα (1491.68 cps/mA), SKα (1724.30 cps/mA), KKα (1198.04 cps/mA), CaKα (295.35 cps/mA), FeKα (57.53 cps/mA), and ZnKα (108.10 cps/mA). The annotated spectrum validates the reliability of the measurements and demonstrates the sensitivity of the technique in detecting both major and trace elements.

IV. Discussion

The elemental characterization of Trigonella foenum-graecum seed powder revealed a balanced profile of macro- and micro-elements, underscoring its nutritional and pharmacological relevance.

Nutritional Significance

The high concentration of potassium (1.15%) highlights fenugreek's role in maintaining electrolyte balance and cardiovascular health. Phosphorus (0.507%) and calcium (0.186%) contribute to bone mineralization and cellular energy metabolism, while magnesium (0.117%) supports enzymatic activity. Sulfur (0.295%) is essential for amino acid synthesis and detoxification pathways. Together, these elements confirm fenugreek's potential as a functional food ingredient.

Trace elements further enhance its nutritional profile. Iron (95.7 ppm) is particularly noteworthy, as fenugreek has traditionally been used to combat anemia. Zinc (43.0 ppm) supports immune function and wound healing, while manganese (16.0 ppm) contributes to antioxidant defense. Copper (15.7 ppm), though present in smaller amounts, plays a role in enzymatic redox reactions.

Toxicological Considerations

The concentrations of trace metals detected fall within permissible limits set by WHO/FAO guidelines for medicinal plants and food products. Importantly, no toxic heavy metals such as lead or cadmium were detected in the sample, confirming the safety of fenugreek seed powder for dietary and therapeutic use.

Comparison with Literature

Previous studies on medicinal herbs using EDXRF have reported similar elemental distributions, with potassium and phosphorus consistently dominant among macro-elements. The iron and zinc levels observed here align with earlier reports on fenugreek's hematinic and immunomodulatory properties. These comparisons validate the reliability of the present analysis and reinforce fenugreek's established role in traditional medicine.

Methodological Strength

The annotated spectrum confirmed distinct peaks for each detected element, demonstrating the sensitivity and accuracy of EDXRF. The use of multiple secondary targets (Mo, Cu, RX9, Si) under helium atmosphere optimized detection across a wide energy range. This methodological rigor ensures that the reported concentrations are both reproducible and precise.

V. Conclusion

This study successfully applied Energy Dispersive X-ray Fluorescence (EDXRF) spectroscopy to quantify the elemental composition of *Trigonella foenum-graecum* (fenugreek) seed powder. The results demonstrated the presence of essential macro-elements such as potassium, phosphorus, calcium, magnesium, and sulfur, alongside trace elements including iron, zinc, manganese, and copper. The concentrations observed confirm fenugreek's nutritional value, particularly its role as a source of potassium, iron, and zinc, which are critical for cardiovascular health, hematopoiesis, and immune function.

Importantly, no toxic heavy metals were detected, and the trace element levels were within permissible limits set by international food safety standards, underscoring fenugreek's safety for dietary and medicinal use.

The annotated spectrum validated the reliability of the measurements, highlighting the sensitivity of EDXRF in detecting both major and minor elements.

Beyond nutritional and toxicological implications, this work demonstrates the interdisciplinary relevance of physics-based analytical techniques in medicinal plant research. By systematically separating observations into tables and diagrams, the study provides a reproducible framework for future investigations.

Future research should focus on bioavailability studies, nanoparticle interactions, and comparative analyses with other medicinal plants to further explore fenugreek's therapeutic potential. Overall, the findings establish fenugreek seed powder as a model candidate for bridging physics, chemistry, and medicine, and reinforce the utility of EDXRF as a rapid, non-destructive tool for elemental characterization.

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